

Microwave Extraction of Volatiles for Mars Science and ISRU. E. C. Ethridge¹ and W. F. Kaukler², (¹MSFC NASA, Huntsville, AL 35812 ed.ethridge@nasa.gov ²University of Alabama Huntsville, Huntsville AL 35899 william.f.kaukler@nasa.gov).

The greatest advantage of microwave heating for volatiles extraction is that excavation can be greatly reduced. Surface support operations would be simple consisting of rovers with drilling capability for insertion of microwaves down bore holes to heat at desired depths. The rovers would also provide support to scientific instruments for volatiles analysis and for volatiles collection and storage. The process has the potential for a much lower mass and a less complex system than other in-situ processes. Microwave energy penetrates the surface heating within with subsequent sublimation of water or decomposition of volatile containing minerals. On Mars the volatiles should migrate to the surface to be captured with a cold trap. The water extraction and transport process coupled with atmospheric CO₂ collection could readily lead to a propellant production process, $\text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{CH}_4 + \text{O}_2$.

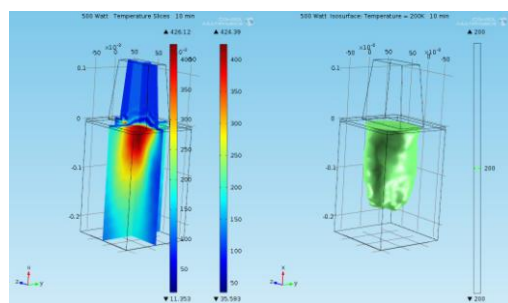
For the past 7 years we have been developing the use of microwaves for the extraction of volatiles from regolith. In 2005 we demonstrated the proof of principle that microwaves (2.45 GHz) will couple with lunar regolith permafrost simulant at cryogenic temperatures in a vacuum resulting in rapid sublimation of water and collection on an external cold trap. Recently we completed a 4 year ROSES-LASER project [1]. Experiments included heating of a simulant bed with a microwave horn beamed into the surface and temperatures were measured with fiber optic sensors. The resulting heating is consistent with theoretical calculations.

In order to perform realistic calculations of microwave heating, the complex electric permittivity and magnetic permeability of regolith simulants were measured at 0.9, 2.45 And 10 GHz. Having the regolith materials properties, finite element multiphysics analysis models were developed to simulate the microwave absorption and heating of lunar and Mars regolith simulant.

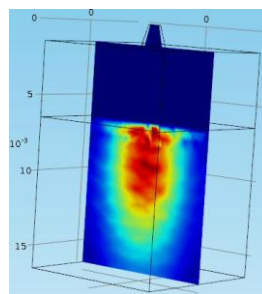
Models for different types of microwave launchers have been developed to test simulations of different kinds of experiments and processing conditions. Calculations at different microwave frequencies illustrate the dramatic difference in depth of heating. Lower frequencies penetrate deeper while the higher frequencies heat shallower depths to much higher temperatures.

The simplest microwave delivery method is to beam the energy into the surface with a microwave horn. A bore hole is not necessary. This method could

be useful for analysis of water concentrations in the shallow subsurface of Mars. The figure below illustrates the heating of the lunar surface with an initial temperature of 100K. Microwaves (2.45GHz) from the horn penetrate and heat the regolith. A planar slice illustrates the heating with color isotherms. On the right, is an isothermal surface containing a volume heated 100K above the initial temperature. Essentially all of the water ice within this volume would sublime.



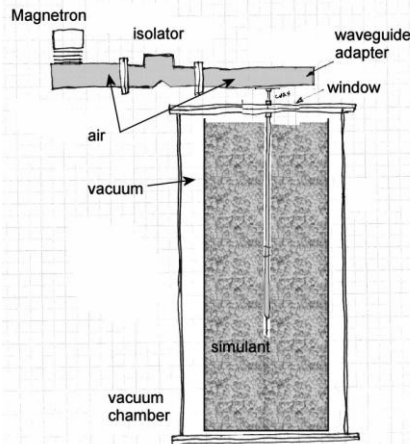
Minerals containing volatiles could be heated to higher temperatures and decomposed using higher microwave frequencies. Parameterization of the FEM model geometry can permit more rapid development of models at different processing frequencies. An example is shown in the next figure, a simulation of a 24 GHz microwave horn to beaming 100W into a 1 cm cube. The temperature slice after 30 min shows temperatures from the initial 100K to greater than 1500K.



Knowing the temperature dependence of mineral decomposition (from DTA and TGA), it should be possible to predict the volatilization rate from the heated volume with time. This in-situ thermo-gravimetric simulation is under development. Theoretically, the largest constraint would be the power available to heat the minerals to the decomposition. Flight qualified TWT amplifiers have greatly increased in efficiency in

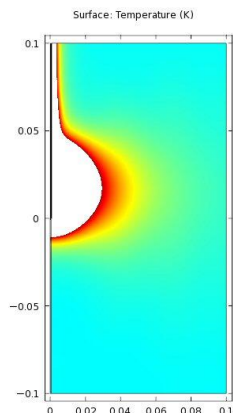
recent years (~50%) and higher efficiency solid state amplifiers are said to be under development.

Recently we have been performing experiments to heat regolith with microwave (2.45 GHz) probes down boreholes to demonstrate volatiles extraction from depths (>1m) below the surface.



Our current experimental setup has the vacuum system contained in a -77C scientific freezer that can simulate Martian conditions. Microwaves are delivered down a borehole to depths where water ice could be present. Heating at progressively deeper levels within the borehole would permit the determination of water concentrations with depth. Calculation of volatile mass flow rates is being developed to use with existing numerical models.

Assuming a drilling apparatus could provide the bore hole, microwaves could be delivered to significant depths (>3m) to determine water concentrations. The figure below shows an axi-symetrical EM heating analysis for illustration. The probe (down a borehole) is on the left, the Martian surface is up, and microwaves are emitted from the end of the probe. The regolith heats



radially with processing time. The diameter of the heated volume will be a function of the microwave frequency and time.

Systems could be designed to mine water from depths greatly exceeding those accessible by other ISRU capabilities since the overburden would not have to be removed.

A significant advantage of FEM numerical multiphysics analysis is that parametric analysis of different experimental processing conditions can be simulated prior to expending the time and expense of experiments at different frequencies. FEM Multiphysics parametric analysis (power, frequency, regolith porosity, temperature) will permit the simulation of experiments, design of experimental hardware, and optimization of planetary surface extraction scenarios. The expected power required to extract a unit mass of volatile could be estimated. The FEM analysis could be used to select the most appropriate processing parameters and define the hardware for volatiles extraction protocols. Ground based experiments could be designed to test the methods of extraction and to validate the numerical multiphysics analysis in a relevant planetary (Mars) testbed facility (at MSFC).

These methods address Challenge Area 1: Near term Instrumentation and Investigation Approaches for interrogating the shallow subsurface of Mars with surface probing of the top 10 cm or so. Also, it would be possible to evaluate water concentrations down to 3m or deeper using boreholes. The methods represent light weight and potentially low cost in situ methods that could be used to extract, identify, and triage high priority volatiles, especially H-ISRU. It also addresses Challenge Area 2: ... Innovative Exploration Approaches. These microwave heating and volatiles extraction methods are relevant to MEPAG Goal 2A to characterize potential key resources including water to support ISRU. The volatiles prospecting and extraction techniques are directly adaptable to the Strategic Knowledge Gaps of Mars exploration. They are also applicable to volatiles extraction from the Lunar pole and asteroidal bodies. The light weight and low cost volatiles extraction techniques are suitable as secondary payloads to be carried on larger landed vehicles. Ground based experiments can be designed to test the methods of extraction while numerical multiphysics analysis could be performed to predict the extraction efficiencies.

References:

[1] Ethridge, E.C. and Kaukler, W. F. (2012) *AIAA Aerospace Sciences Meeting, Nashville, TN.*

Microwave Extraction of Volatiles for Mars Science and ISRU

Edwin Ethridge, PhD
Materials and Processes Laboratory
NASA Marshall Space Flight Center
Huntsville, AL 35812

William Kaukler, PhD
Assistant Research Professor in Chemistry
U. of Alabama – Huntsville, AL 35899

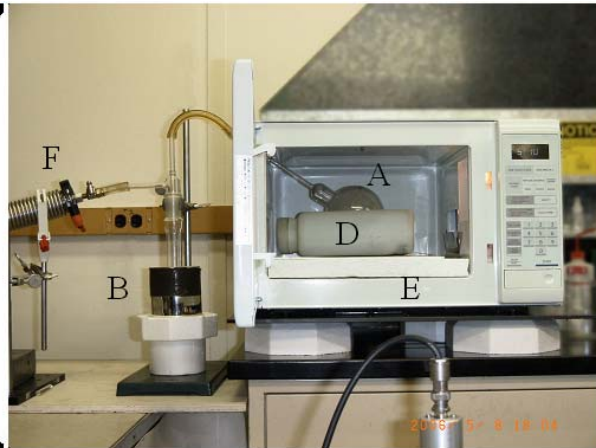
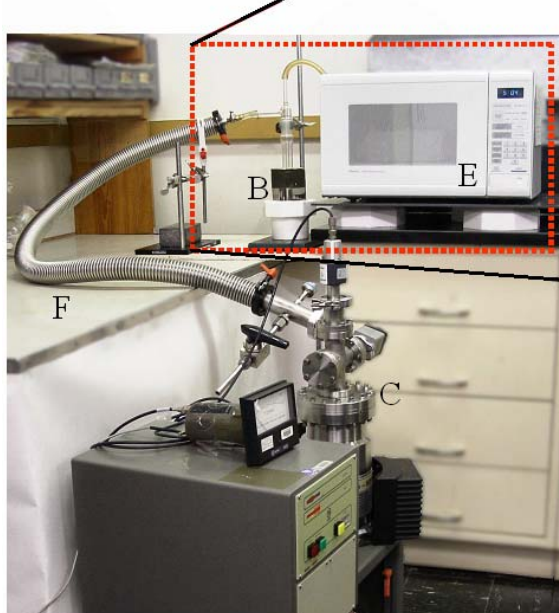


Concepts and Approaches for Mars Exploration
Houston, TX
12 to 14 June, 2012

Advantage of Microwaves for the Extraction of Water and Volatiles

- **Regolith (in vacuum) has a very low thermal conductivity
Low heat flow.**
- **Microwave energy penetrates heating from the inside
Penetration depth is dependent on Frequency.**
- **Heating regolith sublimates water ice**
- **Excavation not be required,
Low experiment mass, less complexity**

Proof of Principle: Water Extraction



Bench top microwave facility

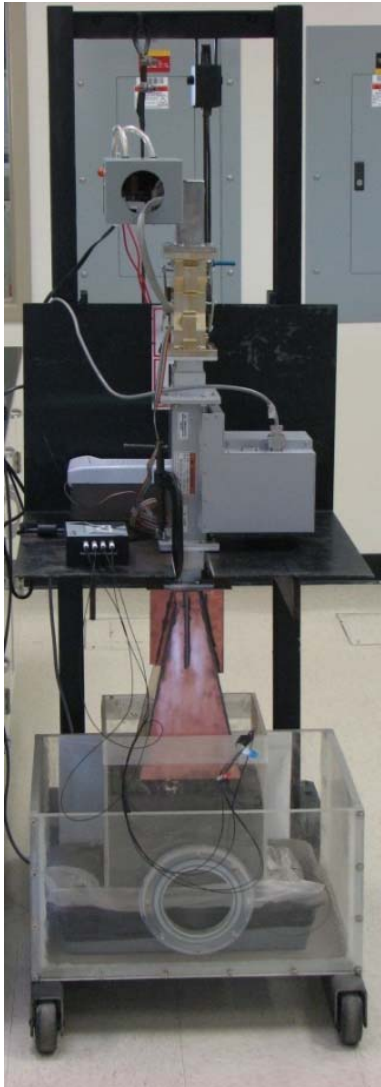
- A. vacuum quartz lunar regolith simulant vessel
- B. liquid nitrogen cold-trap
- C. turbo-molecular vacuum pump
- D. resting in the LN2-cooled regolith bed
- E. microwave oven chamber

- Microwaves (2.45 GHz) couple with and heat regolith simulant (JSC-1A) at cryogenic temperatures,
- Water ice rapidly sublimates $<0^{\circ}\text{C}$.
- Water ice efficiently recaptured on an external cold trap

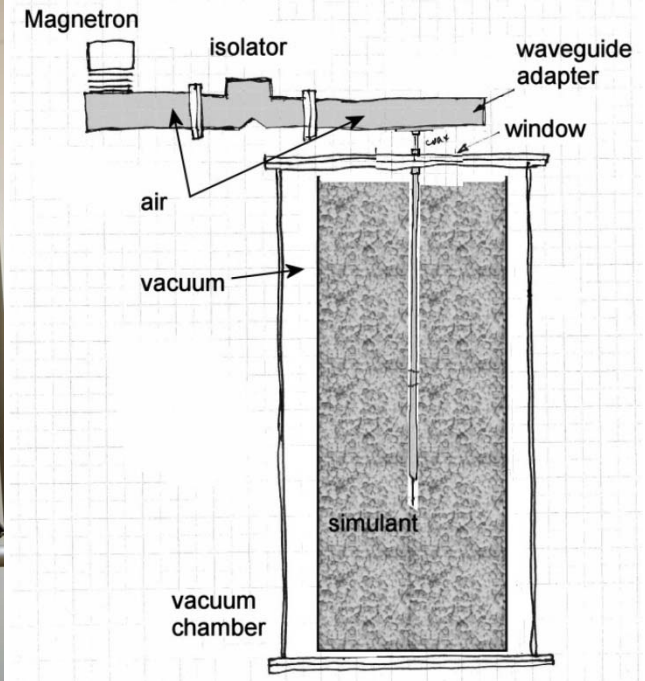
Microwave Demonstration Experiments

2.45 GHz, 500W, isolator, auto-tuner

Microwave Horn



Microwave Heating Down a Borehole Vacuum Chamber in -77K Freezer, Mars Conditions



Temperature measured with 4 Luxtron fluoro-optic sensors
Heating is consistent with Beer Lambert law attenuation.

Property Measurements

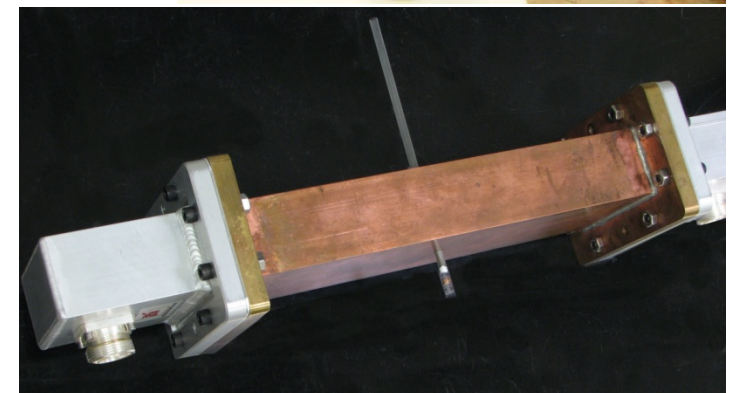
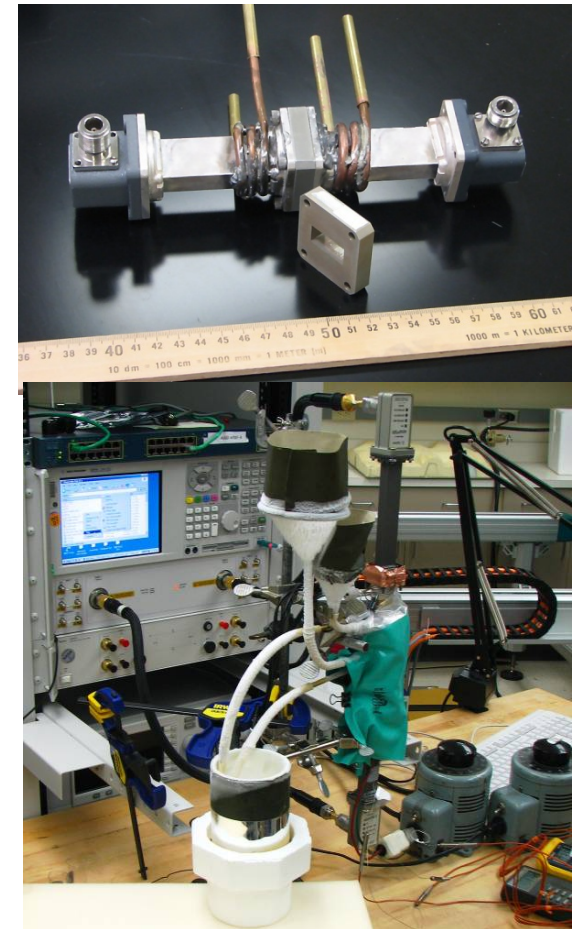
MSFC Microwave Characterization Lab

- Developed methods :
Transmission in waveguide
Resonant cavity

Electric permittivity; $\epsilon' - \epsilon''j$

Magnetic permeability; $\mu' - \mu''j$

- Different lunar and Martian simulants
10GHz, 2.45 GHz, and 0.5 GHz
RT “cryogenic” temperatures



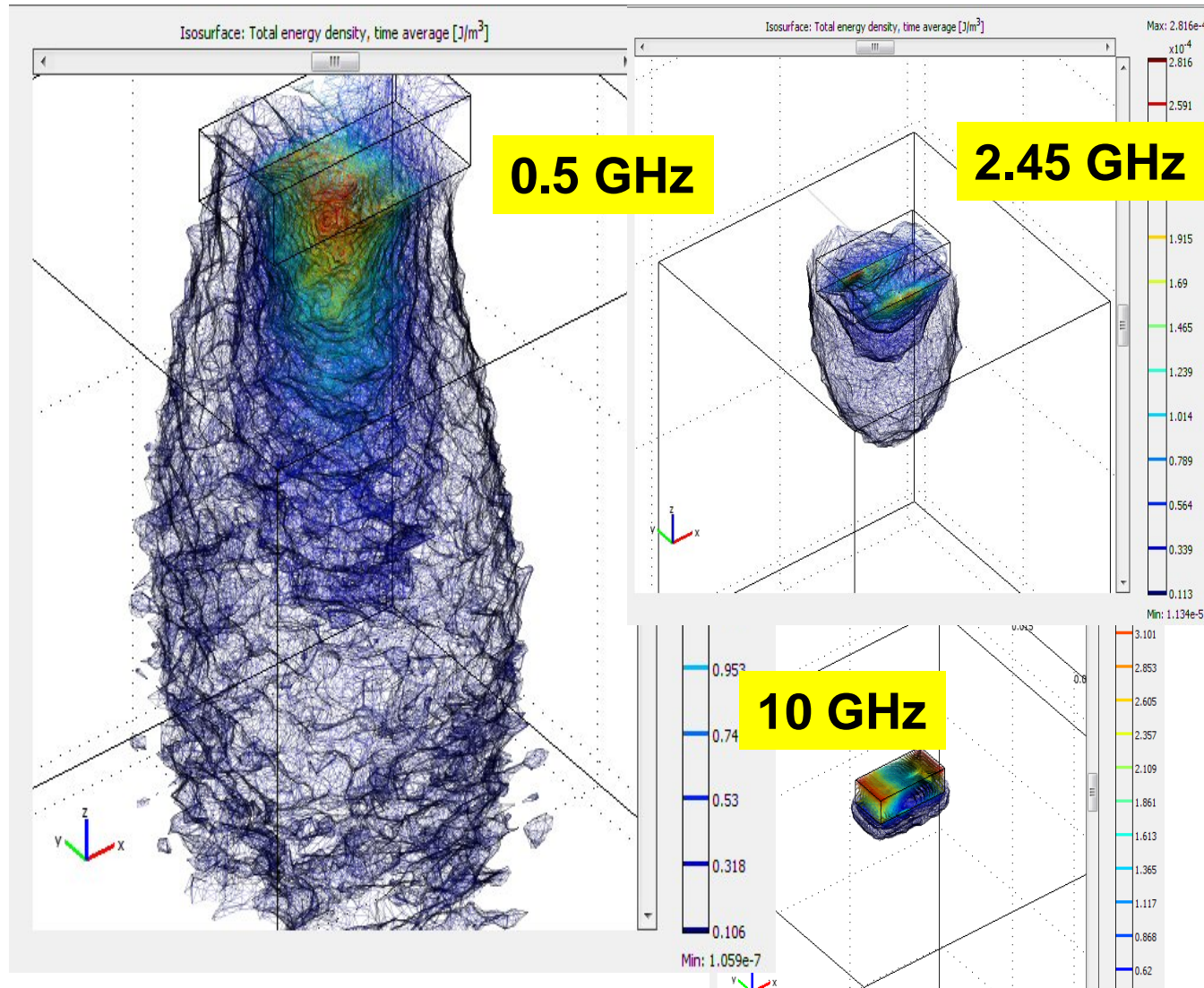
Numerical Analysis of Microwave Heating

COMSOL* Multiphysics

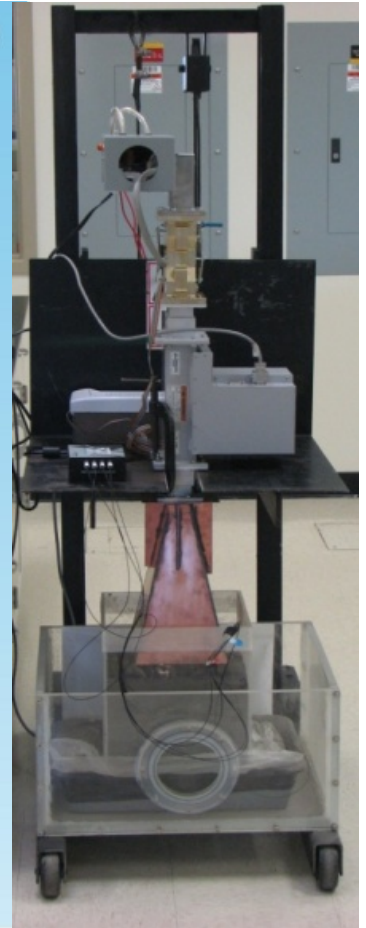
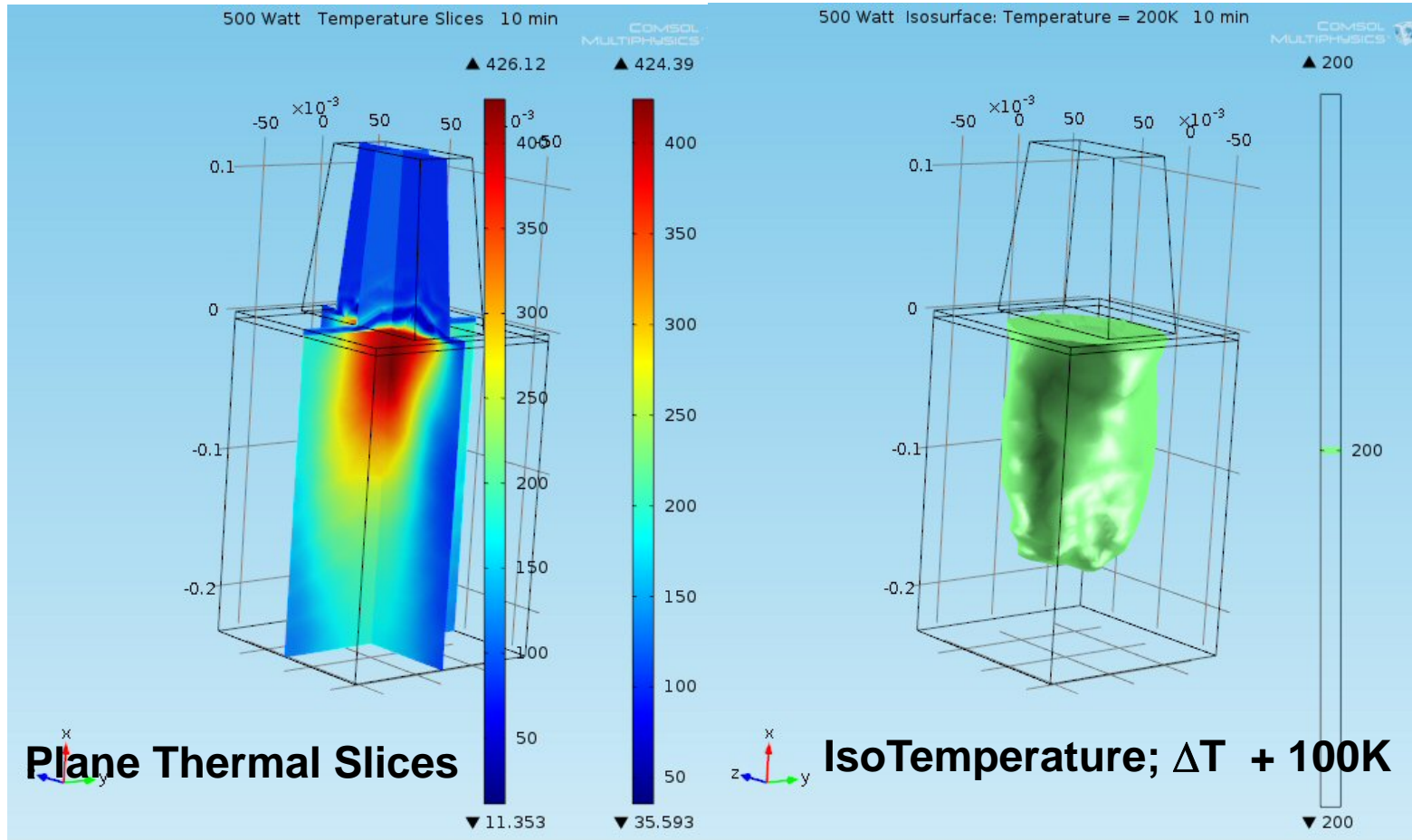
- **Experiments (different frequencies) are expensive and time consuming.**
- **Microwave water (volatiles) extraction is a complex multiphysics problem.**
- **Microwave coupling to materials and heating is dependent on frequency and materials properties.**
- **Materials properties are a function of frequency and temperature.**
- **Can calculate microwave penetration and heating, at different frequencies, with temperature dependent regolith properties.**
- **Can model sublimation and water vapor percolation through the soil (porous media).**
- **Parametric modeling will permit the evaluation of processing parameters most suitable for prototype hardware development, numerical experiments, and trade studies.**

*COMSOL (COMputational SOLutions), Boston, MA

COMSOL RF Module and Heat Transfer Module



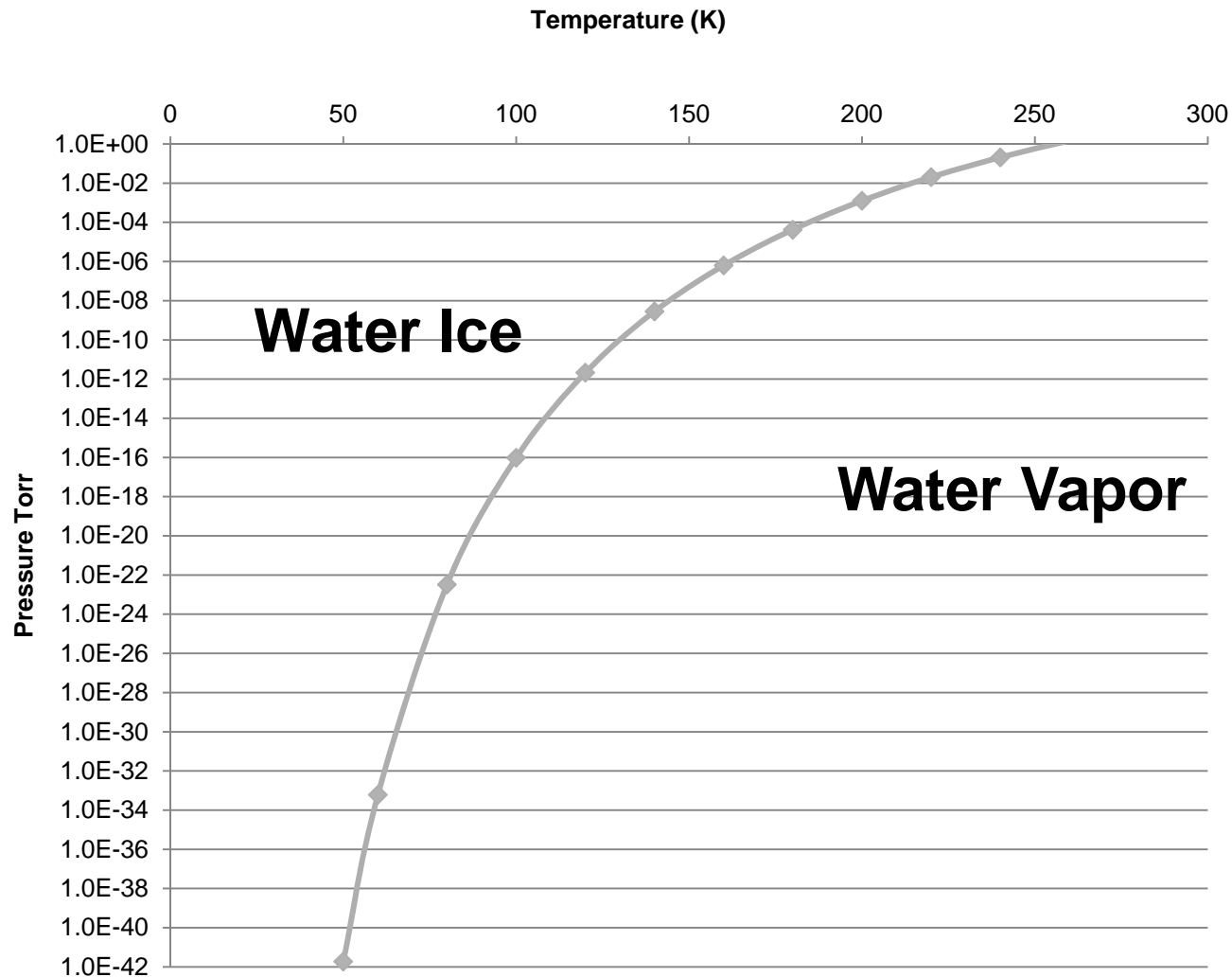
High Gain Microwave Horn 2.45 GHz



Power of 500 watt, Plane slices showing heating into the surface.

Isotherm for ΔT increase of 100K Volatilization of water ice in the volume.

Sublimation Pressure (torr) vs Temperature (K)

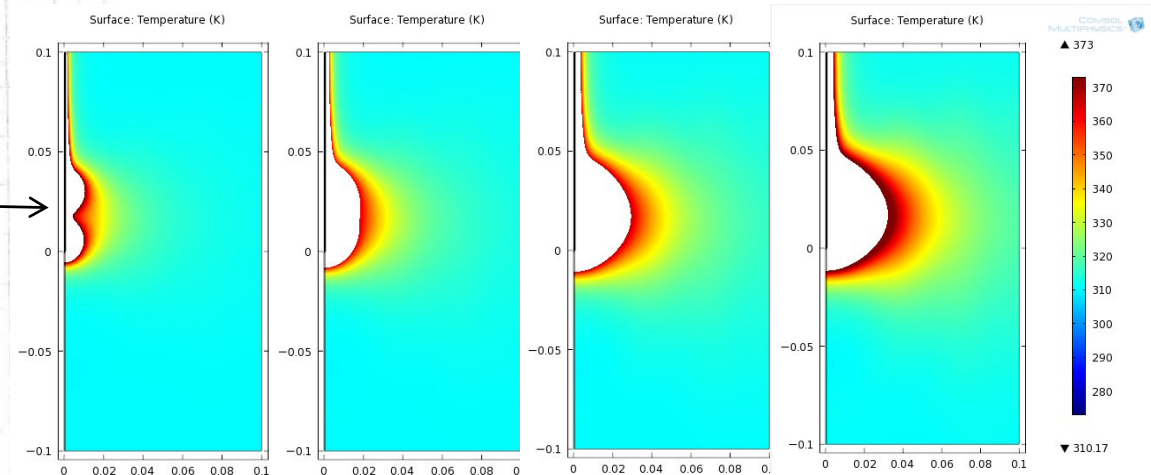
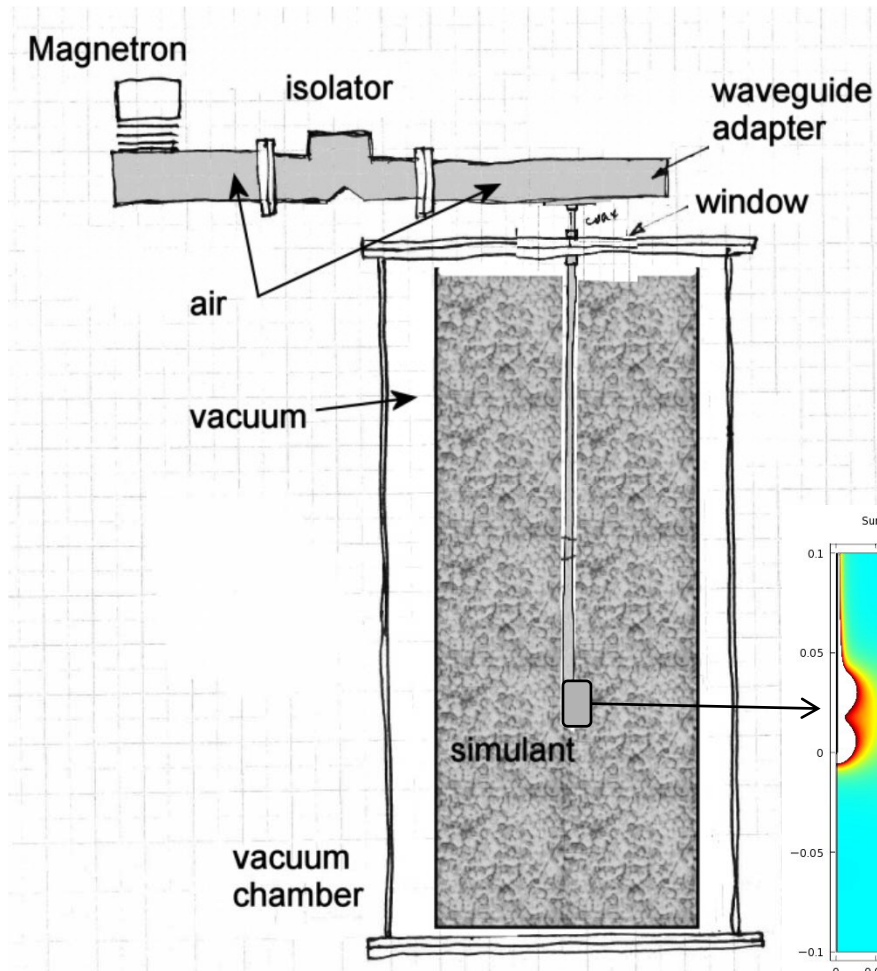


Cooper, J.R. and R.B. Dooley, "Revised Release on the Pressure Along the Melting and Sublimation Curves of Ordinary Water Substance," Inter. Assoc. Prop. Water and Steam (2008).

Localized Microwave Heating Down a Borehole

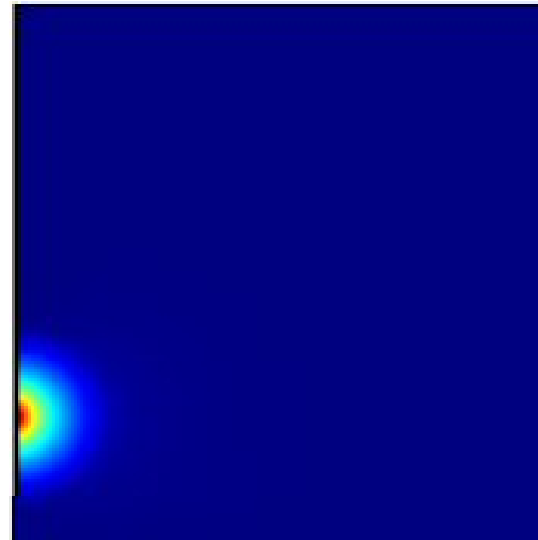
**Relative Concentration and
Depth of Water (1m, 3m, etc.)**

Asxi-Symetric Heating Calculations



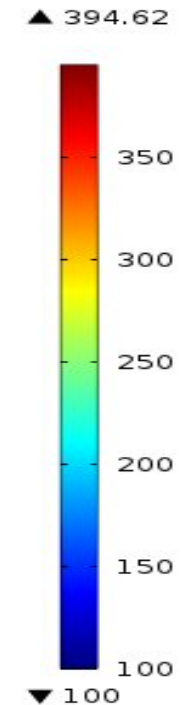
Spherical Heating of Regolith Suitable for Scientific Modeling of Volatization Rates

~3 cm diameter $\Delta T = 100K$



10 min

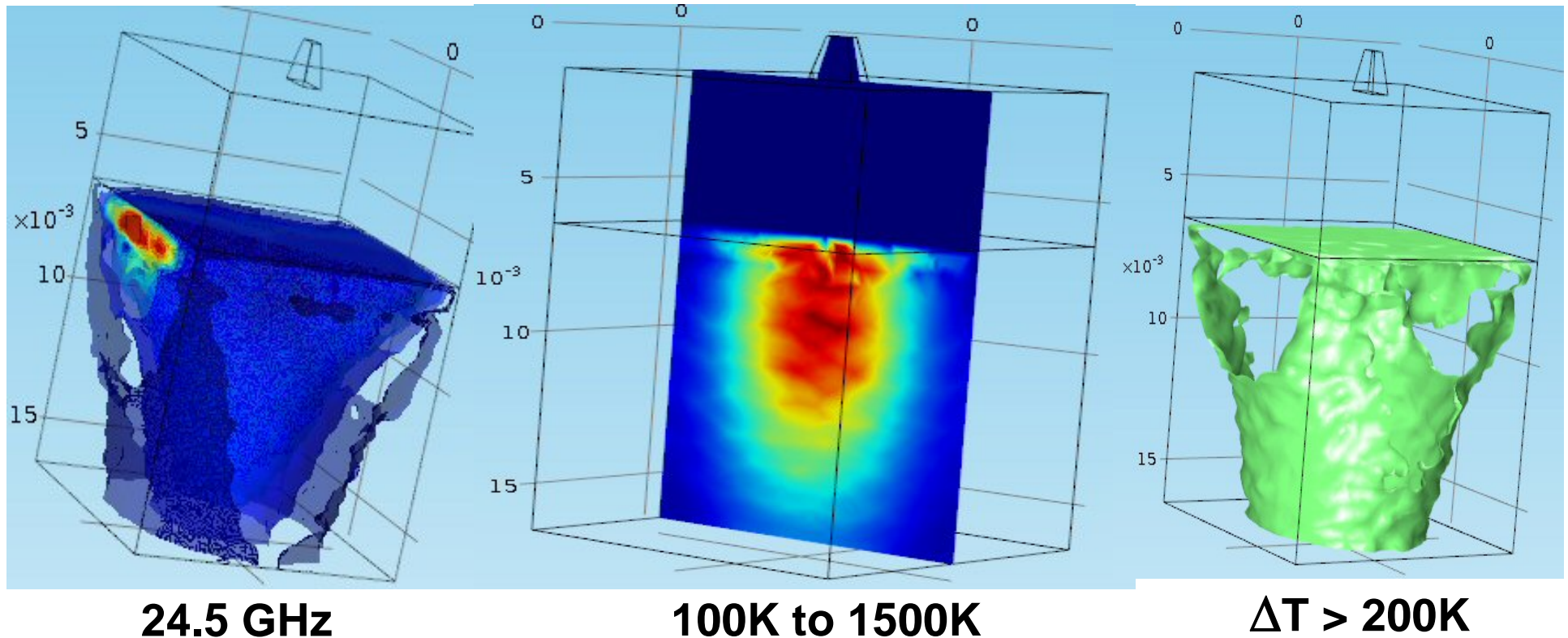
10 cm x 10 cm



Axi-symetrical simulation of 7.14* GHz microwave, 100 W
10 cm squares, Initial Temperature = 100K
Geometry and Applicator – NOT optimized

*X band frequency from the Mini-RF technology demonstrator

Planetary/Asteroid Volatiles Science using High Frequency GHz microwaves



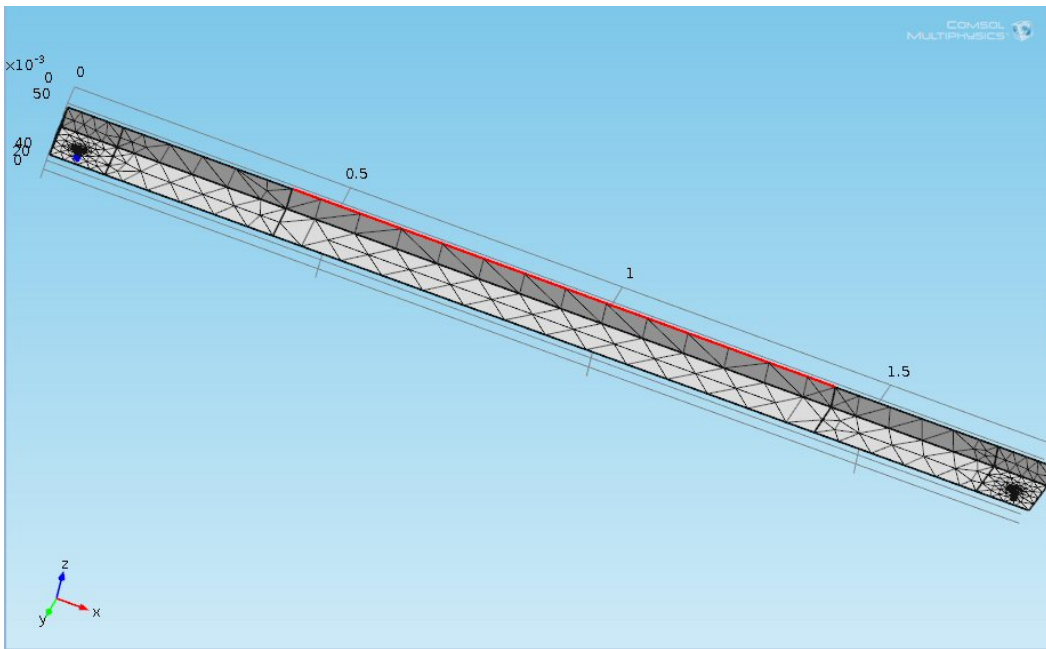
0.5 cm from a planetary surface (1 cm cube volume)
Initial 100K, 24.5 GHz heating (500W).

Color Isotherms within the heating volume,

Possible to study Sublimation, Desorption and Mineral Decomposition To release volatiles from regolith to be detected with sensors on the spacecraft.

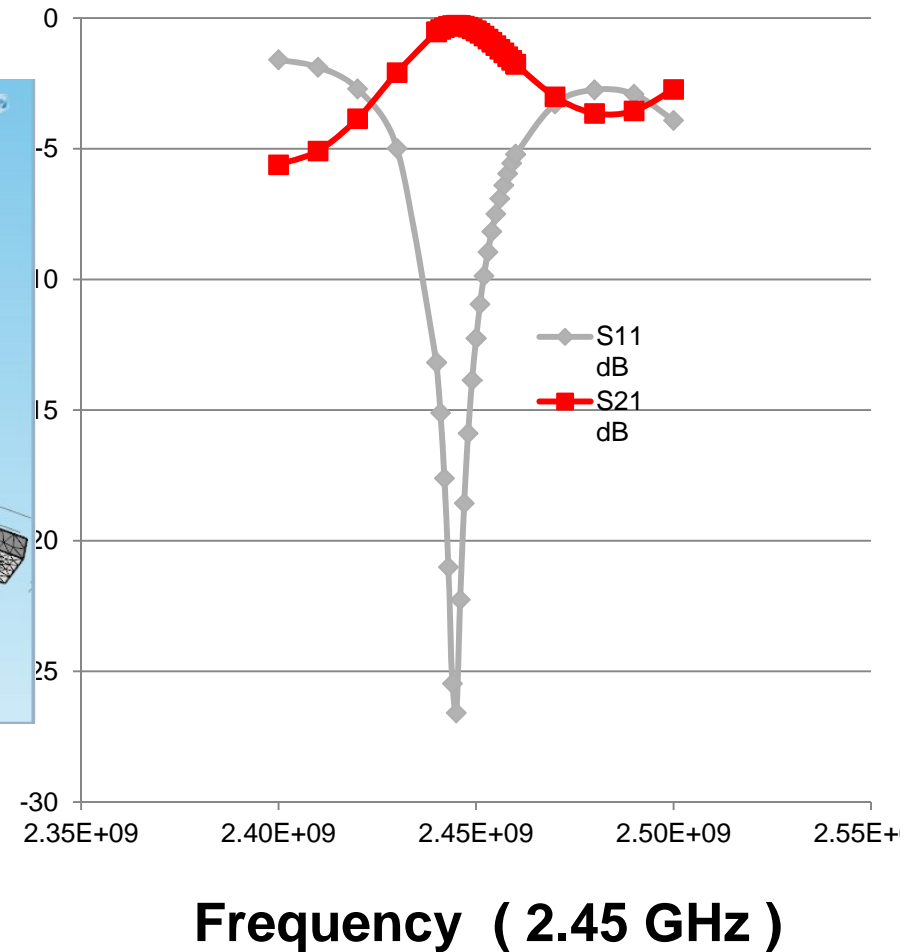
FEM Multiphysics Analysis to Evaluate Designs

TwoWaveguideDualPort(2) 2.45 GHz

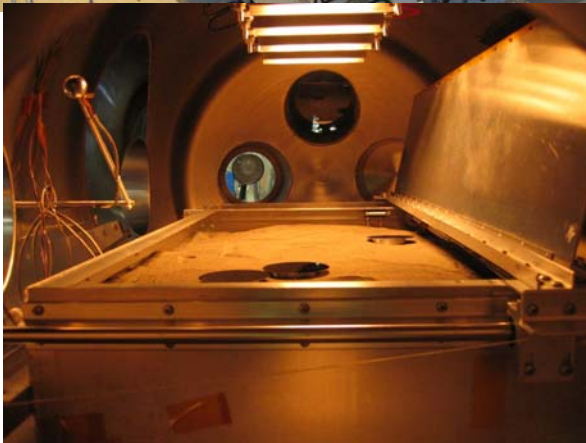
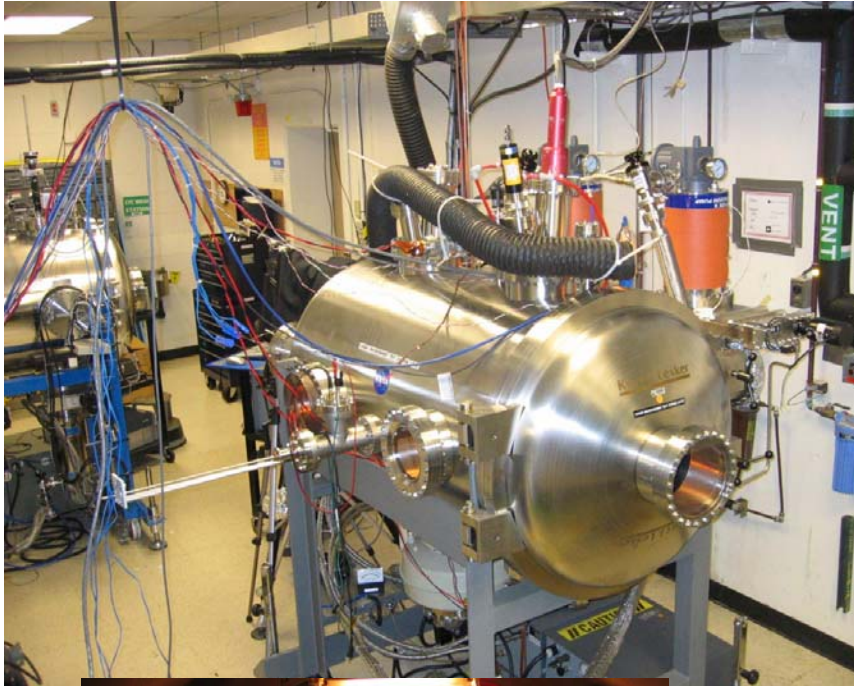


**Hollow 1m Waveguide Power
Reflection Calculations**

S11 dB and S21 dB



Testing in Relevant Environment



**Laboratory Environment Chamber
SWEAP (Solar Wind Electrons Alpha-
particles Protons) Phase B Study**

**Lunar Environment Test Setup (LETS)
Lunar simulant dust migration, charging, etc.**



- Microwaves (2.45 GHz) will **couple with lunar regolith simulants at cryogenic temperatures** and heat to temperatures where water ice will sublime at lunar and Martian conditions.
- FEM Multiphysics models have been developed and **calculations** performed that simulate laboratory experiments. Results are **consistent with the observations from the experiments**.
- The range of the dielectric properties of different regolith simulants that have been measured have a minor effect on the heating of regolith simulant.
- **FEM Multiphysics analysis is useful for modeling microwave penetration and microwave heating at different microwave frequencies, with different microwave launcher designs.** The volume of regolith that is heated sufficiently to completely volatilize the water present in the regolith can be calculated.
- **FEM Multiphysics analysis will be useful for parametric studies of different scenarios for microwave heating of different planetary surfaces for the design of scientific experiments.** It will also permit the design of microwave components and for the determination of hardware requirements for the efficient extraction of water and other volatiles.



Backup Slides



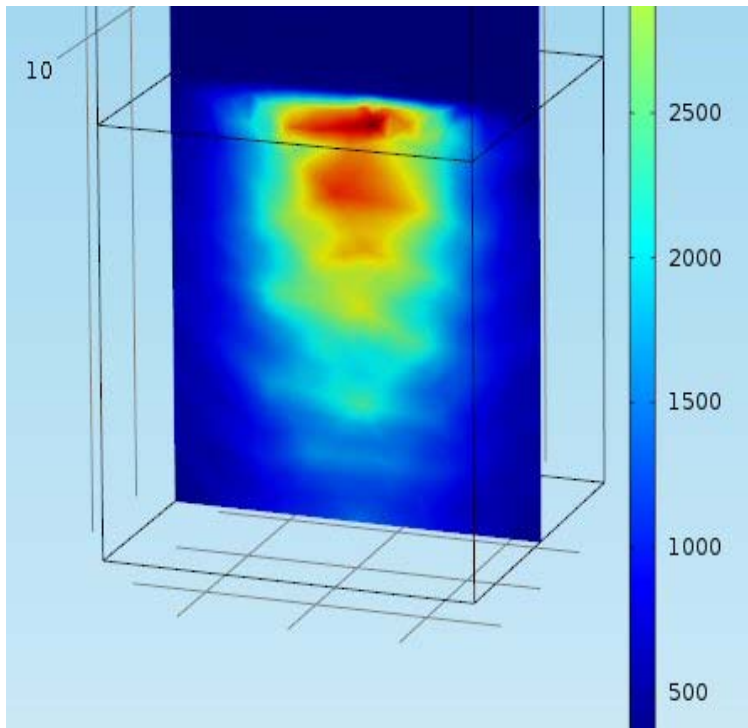


Microwave Melting with High Energy 75 GHz



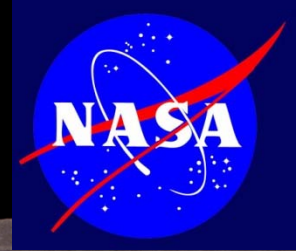
Simplified Physics
High Power Density 3KW/cm²
75 GHz for 2 sec, 3 cm penetration
Temperatures > melting temperature

Samples of lunar (JSC-1 and JS) and Martian (JSC-Mars1) regolith simulants melted with a 35 KW gyrotron device. The narrow microwave beam had a very high flux (~3Kw/cm²). Samples melted in seconds, 3 cm diameter, 0.5 cm thick.





Melting of JSC-1a Simulant



- Conventional Microwave Oven in air
 - Thermal Runaway Heating 5 minutes, alumina crucible
 - No native iron was present.
-
- Bubbles from trapped air in the powder

